Studying Space Plasmas from a Lunar Base

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During the late 1960s and early 1970s, space plasma physics research on and near the moon thrived, with several satellites operating in lunar orbit and several sets of instruments arrayed on the lunar surface. The moon was found to be a uniquely "clean" plasma physics observatory when compared with all other celestial bodies visited by spacecraft. Having no atmosphere and no intrinsic magnetic field, and no induced magnetic field because of its very poor electrical conductivity, it provides little advance warning of its presence to approaching space plasmas which, therefore, impinge directly on its surface. Magnetic lines of force from external sources thread through the moon in a rectilinear manner almost as though it did not exist. It is anticipated that space plasma physics will remain an active discipline when a lunar base becomes possible, and that the moon will be the site of much important research whose exact nature is impossible to foresee.

Introduction

PLASMA physics in general, and space plasma physics in particular, is a very active and rapidly evolving scientific discipline. Thus it would be extremely presumptuous to claim to predict the state of that discipline in 20 years (when manned lunar bases may first become possible) and what the important problems of plasma physics will be then. It is certain, however, that the physics of plasmas will bear a continuing and probably increasing relevance to human activities for the foreseeable future, since much of our advancing technology (e.g., nuclear and space weapons, fusion energy, lasers, space travel) involves that ionized state of matter.

The environment of space offers opportunities to study important aspects of plasmas that cannot be studied on Earth. This is because the plasma encountered in space around the Earth (and at the moon) is very tenuous, with number densities a hundred-billion times smaller than can be achieved in the best laboratory vacuum system. A result of this is that the ions and electrons in the plasma hardly ever collide. Therefore, many aspects of their behavior are more amenable to mathematical modeling and understanding. Very sophisticated instruments can be carried into space to provide much more detailed measurements of particle distribution functions than can be made in laboratory plasmas. Then, too, laboratory plasma experiments often involve very short temporal and spatial variations of the plasma (e.g., microseconds and millimeters), whereas the time and distance scales are typically much longer in space plasmas, allowing measurements of them to be more precise.

The moon, specifically as a base for space plasma research, offers the obvious advantage over spacecraft that experiments of much greater sophistication, e.g., in experiment size, multiplicity, complexity, and (in the case of a manned base) personal attention, will be possible. Problems may, of course, be presented by the moon's large size, obstructing fields of view of various detectors, and by particle, electrical, and magnetic contaminations it may impose on the environment. But, scientific research being the serendipitous activity that it is, it should not be surprising to find that many of these "problems" can be turned into useful tools of research; as we shall see, some have already.

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This paper will describe some previous space plasma research using the moon not only as a base, but as a research tool and an object of research as well. We then will turn our attention to the environment of the Earth's magnetotail, where the moon spends about four days each month, and will describe some recent important observations there. Finally, we will consider some implications of a manned lunar base for space plasma research. First, however, we must recall features of space around the Earth and the moon's place in this environment.

Space Environment of the Earth-Moon System

The solar wind is a fully ionized plasma whose ionic component comprises mostly protons, but with a few percent of helium and traces of other ions. The solar wind flows con-

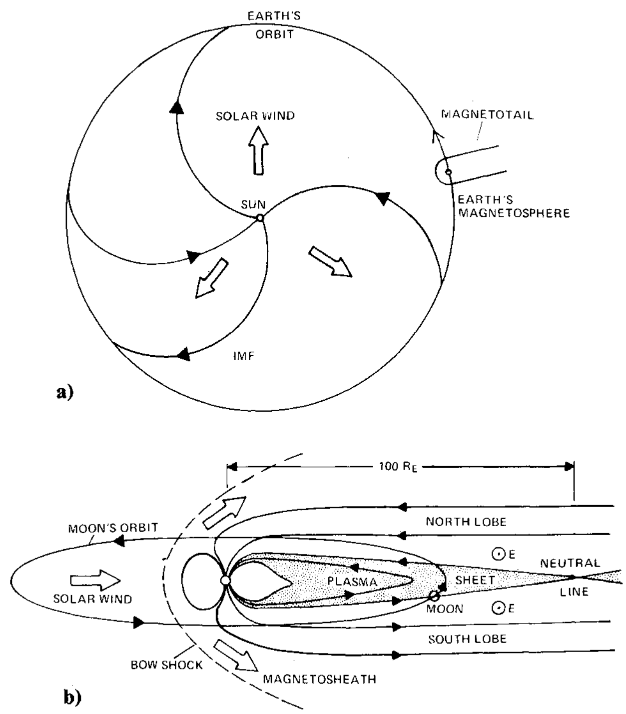

Fig. 1: a) Schematic representation of the inner solar system depicting the solar wind, the interplanetary magnetic field (IMF) lines, and the Earth's magnetosphere; b) The Earth's magnetosphere and bow shock and the moon's orbit (shown nearly edge-on).

tinually from the sun and impacts the Earth's magnetic field, compressing the sunward portion of the field and stretching its antisunward portion downstream to form a comet-like structure, millions of kilometers long, called the geomagnetic tail or magnetotail (see Fig. 1). The solar wind contains a magnetic field of its own—called the interplanetary magnetic field (IMF)—that it carries out from the sun. The cavity in the solar wind that contains the greatly distorted geomagnetic field is called the magnetosphere. A bow shock stands in the flowing plasma upstream of the magnetosphere, and the shocked solar wind flows around the magnetosphere in a region called the magnetosheath. The long cylindrical magnetotail contains a plasma sheet that extends across its $\sim 50R_E$ diameter. (The Earth's radius, $R_E = 6370$ km, will often be used as the unit of distance here.) The plasma sheet is characterized by "hot" plasma of number density ~ 0.1-$1.0/\mathrm{cm}^3$. North and south "tail lobes" lie above and below the plasma sheet and contain "cool" plasma of number density $\sim 0.01/\mathrm{cm}^3$. A magnetic neutral line extends across the tail about $100R_E$ from Earth. There plasma and magnetic field lines, carried in from the lobes by the $\bar{E} \times \bar{B}$ drift due to a dawn-to-dusk electric field, meet. Magnetic reconnection occurs at the neutral line, and plasma jetted earthward by this process maintains the plasma sheet. The moon orbits the Earth at a distance of $60R_E$. Thus, it is in the solar wind about 20 days of each orbit, in the magnetosheath about four days, and in the magnetotail another four days. Within the magnetotail, it samples both the plasma sheet and the lobes. Thus, it is an excellent platform from which to study the diverse components of the solar wind-magnetosphere plasma system.

Previous Space Plasma Research at the Moon

The first opportunity to do extended studies of space plasma in the vicinity of the moon came in 1967, when the Explorer 35 satellite was placed in a lunar orbit. In 1971 and 1972, the Apollo 15 and 16 particles and fields subsatellites (PFS 1 and 2) were put in orbit about the moon. Plasma analyzers, particle detectors, and magnetometers were placed on the moon's surface by the Apollo 12, 14, and 15 astronauts. Thus, for several years, the moon served as a space plasma observatory. A few of the important results derived therefrom are discussed subsequently.

The moon had been known to have no atmosphere. Measurements with Explorer 35[1,2] showed, furthermore, that the moon does not have a large-scale magnetic field, such as the Earth and some other planets do, and that its electrical conductivity is very low so that magnetic lines of force from external sources thread through the moon in a rectilinear manner almost as though it did not exist. It was also found by Lyon et al.[3] that solar wind plasma particles impinge directly onto the moon's surface and are absorbed by it, leaving an empty cavity downstream. To date, the moon is unique among the bodies visited by spacecraft, in thus allowing almost free and complete access of space plasmas to its surface, unimpeded by atmosphere, intrinsic magnetic field, or induced magnetic field. This is, of course, an important attribute if space plasmas are to be studied from a lunar base.

The sharp particle shadow cast by the moon became a useful tool for studies of the magnetotail. During a solar electron event in 1967, the Earth-moon system was immersed in an isotropic homogeneous flux of >50 keV electrons. The electron flux measured by Explorer 35, orbiting the moon in the magnetotail lobe, was usually the same as that measured by another satellite, Explorer 33, that was in the solar wind. However, when Explorer 35 passed along the earthward portion of its lunar orbit, it measured a sharply decreased electron flux. The interpretation (see Fig. 2) was that solar electrons gained access to the magnetotail somewhere tailward of the moon via the lobe magnetic field lines which connect to the IMF. As magnetic field lines moved through the tail lobe under the influence of the $\bar{E} \times \bar{B}$ drift caused by a cross-tail electric field; the moon blocked the electron supply to their earthward ends while those already there struck the moon's surface within a few seconds and were absorbed by it.[4] From the sharpness and size of the electron shadow, it was deduced that the cross-tail electric field at those times was less than 5×10^{-4} V/m.[4]

The idea of using lunar electron shadows to measure the magnetotail electric field was further advanced by Anderson,[5] and the PFS 1 and 2 satellites were designed and placed in lunar orbits specifically to study the magnetotail electric field by this lunar shadow technique. The experiments were successful, providing the first measurements of the electric field in the tail lobes. They showed that electric field magnitudes ranged from 0 to 2 mV/m and were typically directed from dawn to dusk across the tail.[6]

The electrons in the magnetotail are typically guided into the moon's surface by tail magnetic field lines that thread through the moon as if it did not exist. But if there are localized regions of the lunar surface that are magnetized, the resulting distortion of the net magnetic field can cause some electrons to be reflected (see Fig. 3). Such locations of electron reflection were observed by the PFS 1 and 2 satellites, and were identified as due to surface remanent magnetic fields.[7] The measurement of upward-directed electron fluxes thus became an alternate method for global mapping of the moon's remanent magnetic fields.

These surface remanent magnetic fields can strongly perturb the solar wind flow locally near the lunar surface if they are strong enough and/or cover a large enough area. Solar wind spectrometers were operated simultaneously at the Apollo 12 site where the local magnetic field was measured (by a lunar based magnetometer) to be 38 nT, and at the Apollo 15 site where the measured field was only 3 nT. At the Apollo 15 site, the solar wind seemed unaltered from its normal characteristics. But at the Apollo 12 site, substantial deflection and acceleration of the plasma flow was found, effects that

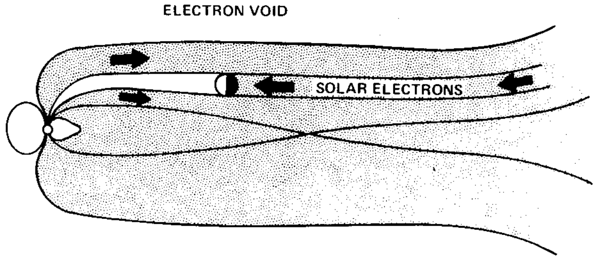

Fig. 2 Illustration of solar particle shadowing by the moon.

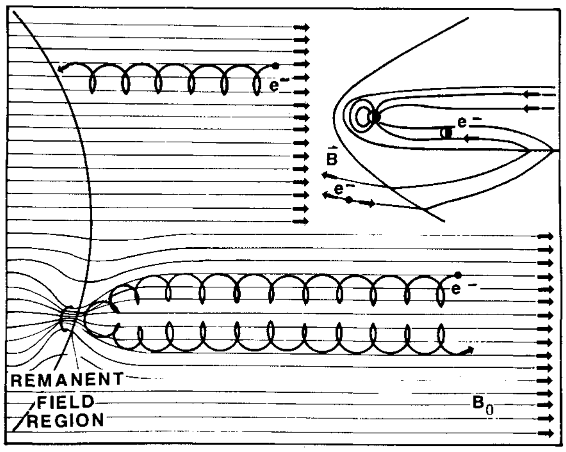

Fig. 3 Illustration of solar electron scattering geometry resulting from combined remanent and tail lobe magnetic fields. The inset shows the route of access of solar electrons to the tail along tail lobe field lines connected to the IMF (Ref. 7).

were ascribed to electric fields caused by charge separation of the incoming solar wind in the relatively strong remanent field.[8]

Rich et al.[9] examined the plasma sheet using data from a charged particle detector at the Apollo 14 site and correlated this with magnetic field data from Explorer 35. They found that the presence of the lunar surface did not appreciably affect measurements of the plasma sheet characteristics by the particle detector. In particular, the lunar surface generally does not shadow plasma sheet particles. This is probably due to the highly variable magnetic field in the plasma sheet as compared to that in the tail lobes, where the electron shadow measurements of Van Allen and Ness[4] and McCoy et al.[6] were done. Geomagnetic activity reduced the probability of encounters between the moon and the plasma sheet, a result that is consistent with the neutral line model of magnetospheric substorms (see subsequent discussion).

Magnetospheric Substorms and Plasmoids

In its interaction with the solar wind, the magnetosphere gains energy and plasma, some of which it dissipates to the Earth and to space around the Earth by various means, some of which impact upon man's activities. For example, electric currents are driven along magnetic field lines from the solar wind into and through the ionosphere. These perturb the geomagnetic field, heat and perturb the ionosphere, and alter thermospheric wind patterns, possibly influencing global weather in some way. Particles are energized to form the Earth's radiation belts; some of these particles precipitate into the atmosphere, altering its chemistry and producing polar auroras. It has been discovered recently that a large fraction of the acquired energy and plasma is returned to the solar wind in the form of large bodies of magnetized plasma, called plasmoids, that are created by magnetic reconnection during magnetospheric substorms and flow swiftly downstream through the tail.

The process of magnetic reconnection was introduced earlier when it was mentioned that it occurs at the distant neutral line, about $100R_E$ downtail, and that the plasma sheet is maintained by plasma jetting earthward from the reconnection region. Reconnection can be thought of as nature's way of resolving the problem that occurs when two bodies of plasma, containing oppositely directed magnetic fields, are pressed together (see Fig. 4). The current sheet separating the two becomes unstable, and the field lines begin to reconnect across it at a magnetic neutral line. The magnetic energy is converted, by $\bar{J} \times \bar{B}$ forces, to kinetic energy of plasma that then jets along the interface.

For many years, it has been known that the auroras, ionospheric currents, and geomagnetic disturbance intensify spasmodically and then relax, doing so every few hours on the average. This phenomenon is called a magnetospheric substorm. It is now quite certain that the cause of a substorm is the creation of a new magnetic neutral line (called the substorm neutral line) in the near tail (about $15R_E$ from Earth) and the ensuing magnetic reconnection there. The reconnection jets plasma earthward, which causes the various perturbations there that characterize the substorm. However, it also severs the magnetic Earth ties of the plasma sheet tailward of the neutral line. This plasma sheet segment is quickly transformed into a configuration of magnetic loops, called a plasmoid, which then speeds downtail and eventually joins the solar wind.[10] This scenario was recently confirmed in a rather dramatic way. In 1983, NASA's ISEE 3 satellite traveled far ($\sim 235R_E$) down the magnetotail, and there it identified the plasmoids passing by after substorms started at Earth.[11] (That was the first time the magnetotail had ever been observed in detail at distances much beyond the moon.) This discovery by ISEE 3 is depicted schematically in Fig. 5.

Note also in Fig. 5 that after the plasmoid departs the plasma sheet tailward of the substorm neutral line remains very thin for many minutes. This situation is terminated when the substorm neutral line suddenly moves rapidly tailward (panel 5) and the plasma sheet earthward of it thickens.

Lunar Surface Observations of Passing Plasmoids

When a substorm occurs and a plasmoid is formed and proceeds downtail, it constitutes a traveling bulge in the plasma sheet because of the plasma from its earthward region piling up on the plasma farther along. Thus, if the moon happens to be near, but above or below the plasma sheet, it can be temporarily engulfed by the thick part of the plasmoid as it passes. Data from the lunar surface and from Explorer 35[9] suggest that this happened at least twice on February 9, 1971. Figure 6 shows geomagnetic records from two stations on Earth (provided by World Data Center A for Geomagnetism). Two very clear substorms appear in these records: one at Churchill just before 8 UT and the other at Chelyuskin just before 16 UT. At these times the moon was traveling through the dusk side of the magnetotail, and is estimated to have been a few R_E above the midplane. Figure 7 shows Explorer 35 measurements of the latitude θ, longitude ϕ, and magnitude B of the tail magnetic field and comet ratio of two channels of the Charged Particle Lunar Environment Experiment (CPLEE) at

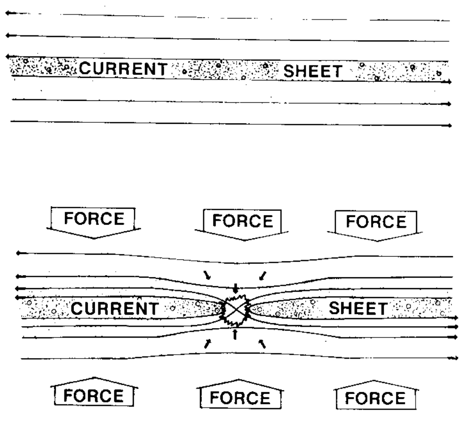

Fig. 4 Illustration of the magnetic reconnection process.

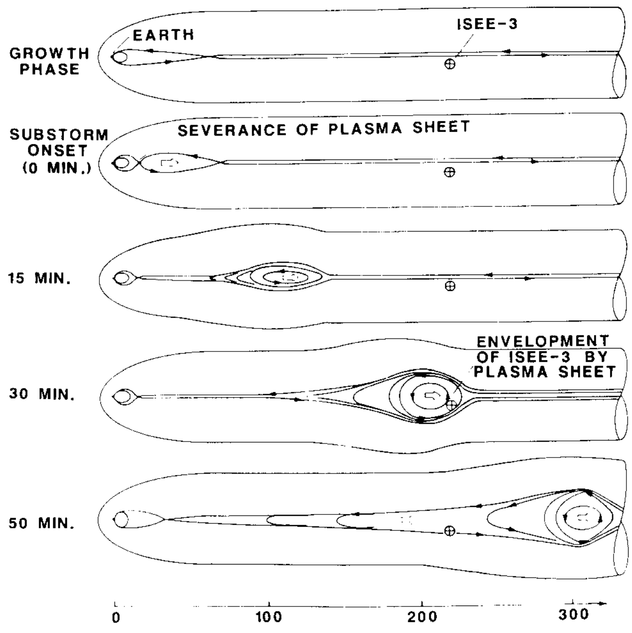

Fig. 5 The quiet time plasma sheet is severed near the Earth by magnetic reconnection at a substorm's onset. It then flows downtail in the form of a "plasmoid" of closed magnetic loops (Ref. 11).

the Apollo 14 site on the lunar surface. This figure (especially the bottom two panels) suggests that the moon was outside the plasma sheet most of the time until 18 UT. But there were occasional entries to it indicated particularly by enhancements of the 2-keV ions. Some of these were probably due to waving motions of the tail due to solar wind variations. But the brief bursts at 8 and 16 UT very likely signify plasmoid passages. Note that the latitude θ of the magnetic field measured by Explorer 35 turned north and then south at the time of the 8 UT event. This magnetic signature is a characteristic of plasmoid passage frequently seen at ISEE 3.[11]

It is notable that the substorm association of these events was not specifically discussed by Rich et al.[9] The subsequent magnetotail studies, especially the ISEE 3 observations, have provided a better understanding of the plasma sheet's substorm behavior and have brought new meaning to these decade-old measurements at the moon. Also notable is the observation of Rich et al.[9] that the moon's probability for plasma sheet encounters was reduced at times of geomagnetic activity. This is now understood as due to the thinness of the plasma sheet that prevails tailward of the substorm neutral line for a considerable time after the plasmoid departs.

Plasma Research at a Lunar Base

The serendipitous character of the plasma research done at the moon (not unlike most scientific research) should be evident in the preceding brief account: The fact of (and usefulness of) particle shadowing by the moon was not explicitly foreseen; the ability to map the moon's irregular surface magnetic field by reflected electrons was not foreseen; and there are many other examples of fortunate unexpected discoveries that were made by accident. And so it will be in the future. To be a little more explicit, let us consider the matter of substorms and plasmoids a bit more, noting ways in which a lunar base might further research in that area.

An array of 20–30 particle detectors and magnetometers distributed over a region several hundred kilometers square on the earthward surface of the moon could measure the envelopment of the moon by plasmoids (as well as by other tail regions and boundaries) and provide a much better idea of their shape, structure, and physical processes than we now have (or will probably have 20 years from now). The tailward end of a plasmoid is thought to lie, typically, beyond the moon's orbit. However, as a plasmoid is released by reconnection near the Earth, the surge of plasma moving tailward creates a bulge in its evolving structure that can temporarily engulf the moon.

A complementary experiment might be done using visible tracer techniques. Figure 8 shows a cloud of barium ions created to trace plasma motions at $\sim 12\text{–}14 R_E$ in the magnetotail. The pictures were taken from Earth with a small telescope. Figure 9 illustrates an analogous experiment that might be used to observe the acceleration and motion of a plasmoid downtail. A satellite would release several kilograms of calcium atoms some $40\text{–}60 R_E$ downtail perhaps 30–60 min before a substorm is predicted to start at Earth. (Substorm onsets can be predicted fairly well from near-Earth satellite data.) The resulting cloud of ions that would be created in about one-half hour by solar photoionization of the atoms

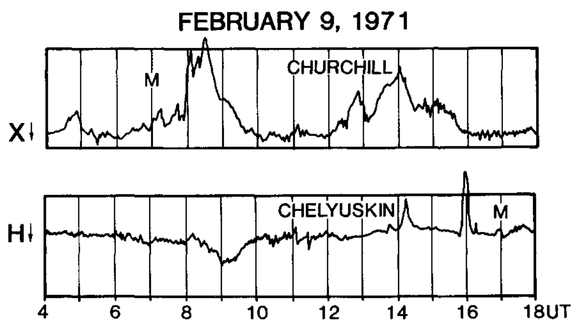

Fig. 6 Magnetograms showing the horizontal component of the geomagnetic field at two ground observatories on February 9, 1971. M indicates the time when the stations are at magnetic midnight.

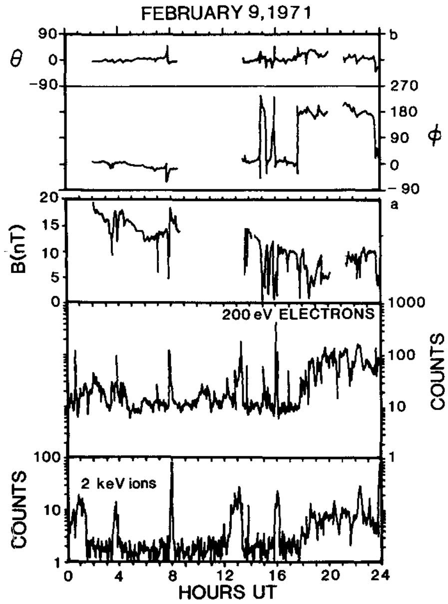

Fig. 7 Data from the moon on February 9, 1971 (Ref. 9).

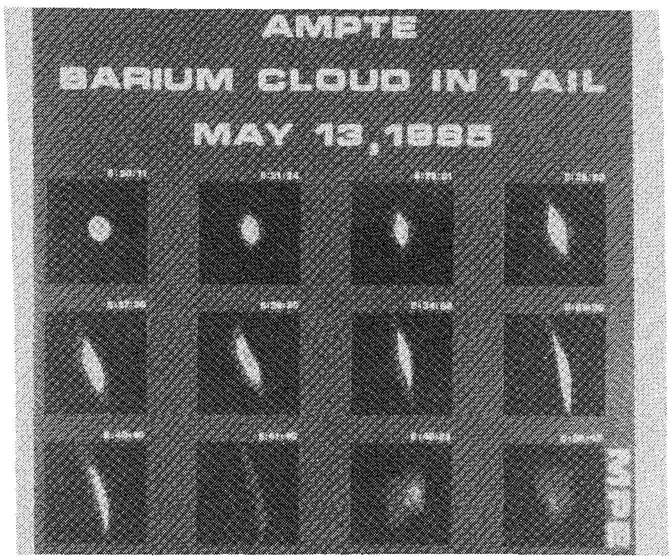

Fig. 8 Phases of development of a barium ion cloud created in the magnetotail 12–14R_E from Earth during the Active Magnetospheric Particle Tracer Explorers (AMPTE) experiment.

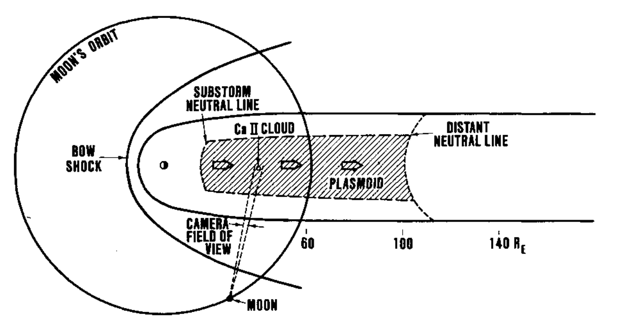

Fig. 9 Conceptual experiment using a calcium ion cloud, viewed from the moon, to trace the development and motion of a plasmoid.

would have a diameter of a few R_E and would be visible from the moon through a telescope with an appropriate optical filter. The motion of the cloud would then be followed after the substorm started, as the plasmoid formed and departed. Performance of such an experiment from the moon offers several important advantages over the analogous experiment done from Earth. First, of course, is the better vantage point the moon offers from which to observe motions in the tailward and earthward directions, which are the directions of principal plasma motions in the magnetotail. Then, too, the very low background light levels available from a lunar base (compared with the terrestrial sky, even from an aircraft) offer a tremendous advantage, as do the possibilities to deploy powerful optics and to use integration times of the order of minutes, as opposed to seconds which have to be used in Earth-based and airborne observations. In recent barium releases, imaging Fabry-Perot systems have been used to investigate the bulk motions and velocity dispersions throughout the various regions of the ion cloud and, thus, to examine effects of various plasma physics processes in addition to the macroscopic velocities and accelerations. Observations from a lunar base would certainly include such advanced techniques as well.

Acknowledgments

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